PB-230 387

NATIONAL EMISSIONS INVENTORY OF SOURCES AND EMISSIONS OF MAGNESIUM

GCA Corporation

May 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

079026

PB 230 387

EPA-450/3-74-010
May 1973

NATIONAL EMISSIONS INVENTORY OF SOURCES AND EMISSIONS OF MAGNESIUM

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Water Programs
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

NC

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-450/3-74-010		PB-230 387

4. TITLE AND SUBTITLE	5. REPORT DATE
National Emissions Inventory of Sources and Emissions of Magnesium	May 1973
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS GCA Corporation GCA Technology Division Bedford, Massachusetts 01730	10. PROGRAM ELEMENT NO. 2AE132
	11. CONTRACT/GRANT NO. 68-02-0601
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Protection Agency Research Triangle Park, N. C. 27711	13. TYPE OF REPORT AND PERIOD COVERED Final
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A national inventory of the sources and emissions of the element magnesium was conducted. All major sources of magnesium-containing emissions were identified and their magnesium emissions into the atmosphere estimated. Also, a method for updating the results of the study every two years was recommended.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Magnesium Air Pollution Emission Inventories Sources		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release Unlimited	Unclassified	40
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	3.25 / 1.45

EPA Form 2220-1 (9-73)

EPA-450/3-74-01

NATIONAL EMISSIONS INVENTORY OF SOURCES AND EMISSIONS OF MAGNESIUM

by

GCA Corporation
GCA Technology Division
Bedford, Massachusetts 01730

Contract No. 68-02-9601

EPA Project Officer: David Anderson

Prepared for

ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Water Programs
Office of Air Quality Planning and Standards
Research Triangle Park, N. C. 27711

May 1973

This report is issued by the Environmental Protection Agency to report technical data of interest to a limited number of readers. Copies are available free of charge to Federal employees, current contractors and grantees, and nonprofit organizations - as supplies permit - from the Air Pollution Technical Information Center, Environmental Protection Agency, Research Triangle Park, North Carolina 27711, or from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22151.

This report was furnished to the Environmental Protection Agency by GCA Corporation, Bedford, Massachusetts, in fulfillment of Contract No. 68-02-9601. The contents of this report are reproduced herein as received from GCA Corporation. The opinions, findings, and conclusions expressed are those of the author and not necessarily those of the Environmental Protection Agency. Mention of company or product names is not to be considered as an endorsement by the Environmental Protection Agency.

Publication No. EPA-450/3-74-010

TABLE OF CONTENTS

SECTION	TITLE	PAGE
	ABSTRACT	v
	ACKNOWLEDGEMENT	vi
I	INTRODUCTION	1
	A. PURPOSE AND SCOPE	1
	B. CONCLUSIONS	2
II	OVERALL U.S. MATERIAL FLOW CHART FOR MAGNESIUM	4
	A. MINING OF MAGNESITE, BRUCITE AND OLIVINE	4
	B. MINING OF DOLOMITE	4
	C. RECOVERY OF MAGNESIUM FROM SEAWATER AND WELL BRINES	4
	D. IMPORTS AND EXPORTS	6
	E. MAGNESIUM OXIDE	6
	F. MAGNESIUM METAL	6
	G. REFRACTORY MAGNESIA	7
	H. MAGNESIUM CHEMICALS	7
III	SOURCES AND ESTIMATES OF MAGNESIUM - CONTAINING EMISSIONS	9
	A. DATA PRESENTATION AND ACCURACY	9
	B. DEVELOPMENT OF EMISSIONS ESTIMATES - 1970	13
	C. SUMMARY OF PRINCIPAL EMISSIONS	20
IV	REGIONAL DISTRIBUTION OF PRINCIPAL SOURCES AND EMISSIONS	21
V	NATURE OF EMISSIONS	25
VI	UPDATING OF EMISSIONS ESTIMATES	29
	A. VERIFICATION OF CURRENT ESTIMATES	29
	B. PERIODIC REVIEW OF ESTIMATES	29
VII	REFERENCES	31

LIST OF TABLES AND FIGURES

TABLE NO.		PAGE
1	SOURCES AND ESTIMATES OF MAGNESIUM-CONTAINING EMISSIONS	10
2	SUMMARY OF PRINCIPAL SOURCES AND EMISSIONS OF MAGNESIUM	20
3	REGIONAL DISTRIBUTION OF PRINCIPAL SOURCES AND EMISSIONS	22
4a	DESCRIPTION OF MAGNESIUM MINERALS AND PRODUCTS	26
4b	PROPERTIES OF MAGNESIUM METAL	26

FIGURE NO.		
1	MAGNESIUM MATERIAL FLOW - 1970	5

ABSTRACT

A national inventory of the sources and emissions of the element magnesium was conducted. The study included the preparation of an overall material flow chart depicting the quantities of magnesium moving from sources of mining and importation through all processing and reprocessing steps to ultimate use and final deposition. All major sources of magnesium-containing emissions were identified and their magnesium emissions into the atmosphere estimated. A regional breakdown of these sources and their emissions was also provided. The physical and chemical nature of the magnesium-containing emissions was delineated to the extent that information was available, and a methodology was recommended for updating the results of the study every two years.

ACKNOWLEDGMENT

The continued cooperation and dedication of Mr. Carl Spangler of EPA, who served as Program Monitor until his death, is deeply appreciated.

GCA would like to extend thanks to Mr. David Anderson and Mr. James Southerland of EPA for their cooperation in the preparation of this study.

In addition, special thanks are also due to Mr. E. Chin, Commodity Specialist, Bureau of Mines; Ms. Marie Harris, Dept. of Commerce; and The National Lime Association, Washington, D.C., who provided significant technical inputs to this program.

I. INTRODUCTION

A. PURPOSE AND SCOPE

The Monitoring and Data Analysis Division, Office of Air Quality Planning and Standards of the U.S. Environmental Protection Agency (EPA) has contracted with GCA Technology Division to conduct a national inventory of the sources and emissions of the element magnesium. The purpose of the study was to define as accurately as possible, based on existing and available published and unpublished information, the levels, nature, and sources of magnesium-containing emissions for defined geographic regions throughout the United States.

The scope of this program is outlined below:

- Develop an overall material flow chart depicting the quantities of magnesium moving from sources of mining and importation, through all processing and reprocessing steps to ultimate use and final disposition as far as the movements can be traced.

- Identify all major potential magnesium-containing emission sources and estimate the total quantity of magnesium emitted to the atmosphere from each source. Emission factors and level, and types of air pollution control, are also provided for each of these sources to the extent that available information permits.

- Define those sources which contribute at least 80% of the total emission of magnesium.

- Provide a regional breakdown of these major sources and their emissions.

- Present the nature of the magnesium-containing emissions for each of these major sources, including a delineation of their physical and chemical form and particle size distribution, to the extent that information is available.

- Provide recommendations as to a methodology for updating the results of this study every two years.

B. CONCLUSIONS

1. Material Flow

Based on all available data, 905,000 tons of magnesium was consumed in the U.S. in 1970, in various chemical and pure forms. The sources of magnesium included sea water and other brines, the mining and importation of magnesite, and the mining of dolomite. By far, the largest portion of the magnesium was consumed in the form of fire brick and other refractory materials, especially within the iron and steel industry. Very little magnesium was consumed as metal, and of this, only about 10 percent was recycled as scrap.

2. Principal Emission Sources

Due to a large emission of flyash from the combustion of coal, and a small yet significant concentration of magnesium in the flyash, the largest source of magnesium emitted to the atmosphere was found to be the combustion of coal. Almost 57% of all U.S. emissions of magnesium was from this source.

Within the magnesium and magnesium compounds industries, the largest source of emissions was estimated to be the production of refractory materials, accounting for 10 percent of the total U.S. emissions. Taken together, mining, processing, and calcining of magnesite and dolomite were estimated to be responsible for about 17% of all U.S. emissions of magnesium.

3. Regional Emissions

The region of the U.S. in which most of the estimated magnesium is emitted is Region 5*(Ohio-Minnesota), with about 33 percent of the U.S. total. The region in which the total emission per square mile is greatest is Region 3 (Pennsylvania-Virginia). Although the emissions from these areas are strongly weighted by the estimated emission from coal combustion, similar conclusions would be made in the absence of coal combustion emissions.

*See page 21 for a list of regions.

4. Nature of Emissions

Magnesium is believed to be emitted predominantly in the carbonate and oxide chemical forms, usually not alone but included in most particles along with ash, slag, and other mineral material. A wide size range of particles containing magnesium is generated. However, after particulate control equipment, and/or gravitational settling, the remaining particles containing magnesium are typically on the order of 1 micron diameter. With regard to the magnesium content of these particles, they probably tend to be both stable and relatively inert.

5. Degree of Control

The overall level of control of magnesium emission is estimated to have been about 87 percent in 1970. All of the large sources of emissions were controlled at levels ranging from 82 to 99 percent. Of these large sources, coal combustion, the largest, was also one of the most poorly controlled at an estimated 82 percent. The production of refractory materials was estimated to utilize a control level of only 80 percent.

II. OVERALL U.S. MATERIAL FLOW CHART FOR MAGNESIUM

Figure 1* presents a flow diagram depicting the total quantities of magnesium products moving from sources of mining and importation through the processing and reprocessing steps to ultimate use and final deposition. Each of these sources is discussed below. Process descriptions are given in Section II.

A. MINING OF MAGNESITE, BRUCITE, AND OLIVINE

Magnesite and brucite are presently mined at only the basic open-pit mine in Gabbs, Nevada. Total ore production in 1970 was 631,000 tons.(1) Based on an approximate magnesium content of 35 percent, the magnesium content of the produced ore is estimated at 221,000 tons. Operations at or near the mine, after removal of a large overburden, include blasting, crushing, screening, washing, and drying.

Olivine, another magnesium ore, is presently mined in Washington and North Carolina. No data could be found to estimate its production. Its predominant use is as a molding sand in foundries and it is not in demand specifically for its magnesium content. No other magnesium ores are presently mined, except dolomite.

B. MINING OF DOLOMITE

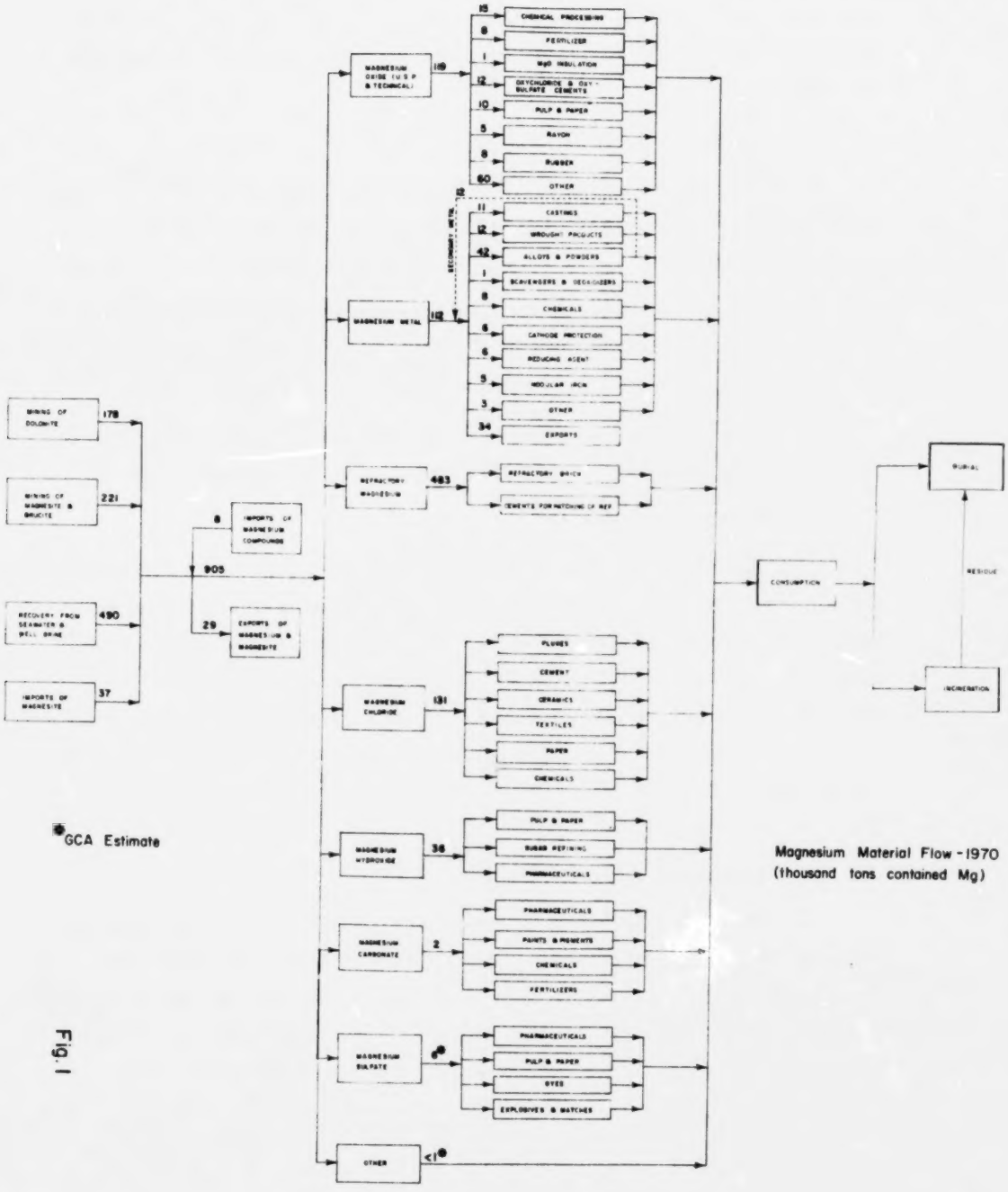
Deposits of dolomite are quarried throughout the United States, using processes similar to the above. It is found extensively with limestone and shares many of the same properties. Total reported production of dead burned dolomite for use as a magnesium compound totaled 1,373,000 tons.(2) Based on a magnesium content of 13 percent, magnesium from dolomite mining totaled 178,000 tons.

C. RECOVERY OF MAGNESIUM FROM SEAWATER AND WELL BRINES

All magnesium metal is produced by electrolysis of magnesium chloride recovered from seawater. In addition magnesia (MgO) and magnesium

---

*Data in Figure 1 and in this section are left unrounded, for purposes of information control. On the average, the typical statistic is accurate to within 10 percent, in the opinion of the authors.



*GCA Estimate

Magnesium Material Flow - 1970
(thousand tons contained Mg)

Fig. 1

chloride recovered from seawater are used to produce other magnesium compounds. The total reported recovery of magnesium compounds (MgO equivalent) from seawater and brines is 625,618 tons.[3] Converting to magnesium content, magnesium compounds from seawater and well brines totaled 378,000 tons of magnesium. In addition, 112,000[4] tons of magnesium metal was produced from seawater. Thus, total production of magnesium and magnesium compounds from seawater and well brines was 490,000 tons.

D. IMPORTS AND EXPORTS

Imports of magnesite in 1970 totaled 128,193 tons.[4] Converting this into total contained magnesium, assuming a 29 percent magnesium content[5] gives an import of 37,000 tons.

Total contained magnesium in imported magnesium compounds reached 8,000 tons, predominantly in the form of epsom salts (magnesium sulfate).

U.S. exports of magnesium and magnesium-containing materials totaled 98,937 tons[2,4] or 29,000 tons of contained magnesium.

E. MAGNESIUM OXIDE

Magnesia (magnesium oxide) consumed other than in refractories and in the production of other magnesium compounds is reported at 198,000 tons (119,000 tons of contained Mg).[5] It is produced predominantly from seawater and well brines by calcining. A primary use is as a stabilizing or vulcanizing agent in rubber. Chemical manufacturers use it in the production of roofing cement. The distribution of uses appearing in the flow chart is based on a percentage breakdown provided by the U.S. Bureau of Mines.[2]

F. MAGNESIUM METAL

Magnesium metal is presently produced solely from seawater, although it has been recently, and may possibly in the future be produced from dolomite in a thermic process. By far the major consumptive use has been in the production of alloys. Its uses are divided between structural and nonstructural. Major nonstructural uses

include use as a reducing agent and for cathodic protection of other metals, particularly iron and steel, in underground pipes, water tanks, and water heaters. The predominant structural consumers are the aluminum industry, which uses magnesium in the production of alloys; and Volkswagenwerk A.G., which uses magnesium extensively in its engines. The distribution in the flow chart is based on data from the U.S. Bureau of Mines.[4]

Secondary magnesium is obtained from new scrap and old scrap. New scrap consists of borings, skimmings, slags, drosses and defective articles produced in mills and fabricating plants. Old scrap is metal recovered from old aircraft and other obsolete equipment. Secondary magnesium is used in alloying, rather than in pure material. Secondary metal production totaled 12,042 tons in 1970.[4]

G. REFRACTORY MAGNESIA

Refractory grade magnesia is produced by high temperature calcining from magnesite, seawater, and from dolomite. It is the major consumption of magnesium compounds, equal to 483,000 tons of contained magnesium.[2] The refractory material is used primarily in steel and nonferrous furnaces for the parts exposed to molten metal and slag. Raw dolomite is also used as a flux and for patching open hearth furnaces. Magnesia is also used in conjunction with chromium to produce chrome magnesite or magnesite-chrome brick.

H. MAGNESIUM CHEMICALS

1. Magnesium Chloride

Magnesium chloride is the primary product from all brines and seawater. According to the Bureau of Mines,[2] 513,029 tons containing 131,000 tons of magnesium were shipped and utilized for non-metal producing uses. It should be noted, however, that almost three times that quantity was utilized as a feed material in the manufacture of magnesium metal, refractory materials, and primary magnesium chemicals.

2. Magnesium Hydroxide

Magnesium hydroxide is a common intermediate product in the production of several magnesium compounds and in metal production.

Its major uses are in sugar refining and pulp and paper, with some use as a pharmaceutical. These three applications consumed 36,000 tons of magnesium.

3. Magnesium Carbonate

Magnesium carbonate is used as a thermal insulator for boilers and pipes, and in table salt to prevent caking, as well as in pharmaceuticals and cosmetics. The total reported to be shipped or used in 1970 by the U.S. Bureau of Mines was 6,799 tons or 2,000 tons of contained magnesium.(2)

4. Magnesium Sulfate

Magnesium sulfate or epsom salt is a major pharmaceutical. It is also used in explosives and matches, in the pulp and paper industry, and in dyes. A major portion (34,939 tons) was imported in 1970. This contained 4,000 tons of magnesium.(2) Magnesium sulfate is also produced from magnesium hydroxide by treatment with sulfuric acid. A total consumption of 6,000 tons of magnesium sulfate was estimated for the U.S. in 1970.

III. SOURCES AND ESTIMATES OF MAGNESIUM-CONTAINING EMISSIONS

A. DATA PRESENTATION AND ACCURACY

Table 1 presents a summary of the data from which emissions were estimated for all major potential sources. Each of the columns comprising this table will be discussed below.

1. Emission Factors

Except where indicated, this gives the pounds of total particulates emitted per ton of production. Such considerations as:

- variations in process conditions among individual plants comprising a source category
- inaccuracies in existing data
- a limited quantity of existing data

may however, result in an average emission factor for a source category varying by more than an order of magnitude from the value presented. In recognizing the need to indicate the level of accuracy of these emission factors, a reliability code is presented along with each emission factor value appearing in the table. This reliability code system is described below and is based on the system utilized in EPA Document No. AP-42, "Compilation of Air Pollutant Emission Factors":[6]

A: Excellent

This value is based on field measurements of a large number of sources.

B: Above average

This value is based on a limited number of field measurements.

C: Average

This value is based on limited data and/or published emission factors where the accuracy is not stated.

D: Below average

This emission factor is based on engineering estimates made by knowledgeable personnel

TABLE 1

SOURCES AND ESTIMATES OF MAGNESIUM-CONTAINING EMISSIONS

Source	Uncontrolled Particulate Emission Factor (lb/ton)	Uncontrolled Particulate Emission Factor (kg/kgx10^3)	Reliability Code	Production Level (tons/yr)	% Mg in Emissions	Mg Emissions Before Controls (tons/yr)	Estimated Level of Emission Control	Mg Emissions After Controls (tons/yr)
MINING & ORE PROCESSING								
Mining, crushing, and drying of dolomite	465	233.0	(C)	2,200,000	13 (A)	66,500	95.0	3,320
Mining, crushing, drying, and briquetting of magnesite	475	238.0	(D)	631,000	40 (B)	59,950	90.3	5,790
OXIDE PRODUCTION								
Dolomite - vertical kilns	7	3.5	(B)	137,300	17 (C)	82	39.0	50
Dolomite - rotary kilns	180	90.0	(B)	1,236,000	17 (C)	18,911	81.0	3,593
Magnesite - rotary kilns	180	90.0	(C)	125,000	50 (C)	5,620	80.0	1,130
Hydroxide - rotary kilns	180	90.0	(C)	625,618	60 (B)	33,700	95.0	1,690
METALLURGY								
Magnesium production	0	0	(D)	136,500		0	0	0
Alloying and refining	4	2	(C)	124,000	60 (D)	149	90.0	15
REFRACTORIES								
Grinding and mixing	150	75.0	(C)	483,000	See Note a.	36,200	80.0	7,250
Electric casting	75	37.5	(C)	44,000	See Note a.	1,650	85.0	250
INADVERTENT SOURCES								
Iron and Steel								
Sinter Process	20 lb/ton sinter	10.0	(B)	51,000,000	0.6 → 6.0 (C)	(3,060 → 30,600) 15,300[b]	90.0	(306 → 3,060) 1,530[b]
Blast Furnace	130 lb/ton pig iron	65.0	(B)	88,800,000	0.1 → 3.6 (C)	(5,770 → 207,900) 69,300[b]	99.0	(58 → 2,079) 693[b]
Open Hearth	17 lb/ton steel	8.5	(B)	65,800,000	0.2 → 0.7 (C)	(1,130 → 3,970) 1,700[b]	40.0	(670 → 2,340) 1,000[b]
Basic Oxygen	40 lb/ton steel	20.0	(B)	48,000,000	0.4 → 0.7 (C)	(3,840 → 6,700) 4,800[b]	99.0	(38 → 67) 48[b]
Electric Arc	10 lb/ton steel	5.0	(B)	16,800,000	0.2 → 9.2 (C)	(168 → 7,700) 4,200[b]	78.0	(37 → 1,700) 924[b]
Coal	N/A	N/A		33,800,000[c]	0.70 (A)	236,000	82.0	42,600
Oil	N/A	N/A		287,000[c]	0.15 (C)	430	0	430
Asbestos	N/A	N/A		6,579[c]	19.0 (A)	1,250	0	1,250
Cement	N/A	N/A		7,790,000[c]	0.07 → 1.15(C)	(5,400 → 89,000) 31,100[b]	88.0	(650 → 10,700) 3,730[b]
Totals						586,842	87.0%	75,293

NOTES: a. Emission factor multiplier equal to tons of Mg processed or handled annually.
b. Intermediate value (see text).
c. Particulate generated, before control. N/A - Not applicable.

2. Level of Production Activity

This column depicts the quantity of material produced (unless otherwise stated) annually. When multiplied by the emission factor, an estimate of the total particulate emissions for that source in pounds per year is obtained.

The values in this column are based on the material flow calculations presented in Section II. Consequently, they have the same accuracy as those material flow values which are estimated at $\pm$ 10%.

3. Percentage of Metal in Emissions

The method of analyzing or assaying a dust sample for the amount of metal it contains determines to a large extent the reliability of the data. For example, analytical chemistry techniques for dust containing substantial fractions of metal can be accurate to within a small percentage. On the other hand, optical spectroscopy methods for determining concentrations or the order of parts per million can be inaccurate by a factor of 2. Because of this variability, the reliability codes discussed above for the emission factors are also utilized to estimate the relative accuracy of the percentage values listed in Column 3.

4. Level of Magnesium Emissions Before Control

The values in this column are derived by multiplying the values in Columns 1 through 3. The result is converted to tons/year of emissions before control.

5. Estimated Level of Emission Control

The overall effectiveness of control for a source category is based on two factors:

- the portion of the processes that are under control
- the typical degree of control

For example, if 60 percent of vertical roasters have some type of particulate emission control and these include both scrubbers and precipitators

such that the apparent weighted average efficiency of control is 85 percent, the overall control effectiveness is estimated to be 60 x 85 = 51 percent.

The accuracy of control efficiency data varies with the degree of control. For a set scrubber operating at 80 percent efficiency (i.e., pass 20 percent material) the actual emission may safely be assumed to be between 15 and 25 percent because of the relative ease of making determinations at this level. Thus, the emissions after control may be assumed to be accurate within $\pm$ 5/20 or 25 percent. On the other hand, for a baghouse reported as being 99 percent efficient, or passing only 1 percent of the material, the actual emission may vary from 0.5 to perhaps 2 percent because it is frequently difficult to make low-level measurements with accuracy. In such cases, the resulting emission data could be in error by a factor of 2.

Unless otherwise specified, it is assumed that the reported overall level of particulate control applies equally to all magnesium-containing particles, independent of size, resistance, and other important collection parameters. This assumption results in a correct estimate of magnesium emissions after control when the particulate is chemically homogenious; i.e., the magnesium is contained in the same concentration in all particles. If however, magnesium is concentrated in certain particles and in addition, the efficiency of the control equipment is not uniform for all particles, then the utilization of an average control level is less valid for calculating magnesium emissions after control. Data on the preferential control of magnesium-containing particles is seldom available, but is included in this report, when possible.

The accuracy of estimating the level of control for a specific source category is dependent on the quality of available data. The investigators feel that, in general, the level of control data will contribute an accuracy to the resulting emission estimates within $\pm$ 25 percent.

6. Level of Metal Emissions After Control

The values in this column are derived by multiplying the values in Column 4 by the value (100 minus estimated level of control).

B. DEVELOPMENT OF EMISSIONS ESTIMATES - 1970

1. Mining of Dolomite

Dolomite and limestone are mined and treated much in the same manner, in that dolomite is the double carbonate of calcium and magnesium ($CaCO_3 \cdot MgCO_3$). Emissions are generated from open-pit mining; crushing and screening; and washing and drying operations, preparatory to burning.

Mining is estimated to generate emissions on the order of 1 lb/ton and is uncontrolled. Crushing and screening are estimated to generate 24 lbs/ton, and since most emissions are uncontrolled, the overall level of control effectiveness is estimated at 20 percent.[7] Drying the washed, crushed rock generates an estimated emission of 440 lbs/ton which is well controlled at an estimated 99 percent.[8] These three emission sources combine to 465 lbs/ton, before control, and 24.6 lbs/ton after about 95 percent control. The typical magnesium content in dolomite is 13 percent.[9] An estimated 2.2×10^6 tons of rock was processed in 1970, of which only about two thirds was converted to magnesium oxide. Further processing of dolomite will be discussed under magnesium oxide production (Section 4).

2. Mining of Magnesite

At present, only one magnesite and brucite mine is operating in the U.S. In preparing magnesite, the steps are similar to dolomite; i.e., crushing and drying. An overburden and waste tonnage equal to twice the magnesite produced, triples the emission up to the point of drying, but simultaneously reduces the magnesium content of the dust by the same proportion. At this mine, the mining, primary crushing, and screening operations are understood to be controlled, resulting in 3,320

tons of magnesium emitted. The drying operation is estimated to be controlled at 96 percent efficiency, resulting in an emission of 2,220 tons of magnesium. After drying, binding ingredients are added to the magnesite concentrate to make it the consistency of heavy dough. It is then pressed into briquettes, and dried in rotary kilns at moderate temperatures. It is next crushed, screened, and stored. The drying and crushing-screening operations are estimated to generate 100 lbs/ton and 25 lbs/ton of emissions, respectively, at 99 and 96 percent control for a net emission of 631 tons of dust or 250 tons of magnesium. Thus, the mine and plant together are estimated to produce a total of 5,790 tons of magnesium emission, after an average control level of 90.3 percent.

3. Recovery From Salt Brines

Sea, well, or lake waters containing magnesium chloride are treated with ground, roasted oyster shell or with a magnesium compound to form a precipitate of magnesium hydroxide. This precipitate is subsequently calcined to MgO (Section 4) or treated and electrolytically separated to magnesium metal (Section 5). Although substantial quantities of precipitate are produced, no emissions are expected except in the case of plants that dry the precipitate for sale or prior to calcining. Emissions from drying in a rotary drier would be expected on the order of 100 lbs/ton, and would be fairly well controlled (90 to 95 percent, probably). However, no data on the drying of precipitate was obtained. It is assumed that any emissions from this process are included with calcining emissions.

4. Magnesium Oxide Production

A variety of oxides are produced for various uses by varying the feed material and the temperature of calcining. Magnesite or MgOH calcined at temperatures below 900°C produces caustic-calcined magnesia, a relatively reactive material used in cements, pharmaceuticals, and the rubber industry. Dolomite is normally calcined at about 1100°C. However, dead-burned dolomite is produced in rotary kilns at about 1700°C, and dead-burned magnesite at up to 1460°C. Dead-burned magnesias thus produced are used largely in refractory materials.

The quantity of emissions from these processes probably depends more on the preparation of the feed material and the type of calcining equipment than on the temperature of operation. Material preparation and equipment used are similar to the lime industry, for which data is more readily available. Emissions factors are estimated at 180 lb/ton for rotary kilns and 7 lb/ton for vertical kilns, with levels of control at 81 and 39 percent, respectively.[6,7,10] It is estimated that 10 percent of the dolomite is processed in vertical kilns, and that all hydroxide precipitate and magnesite are processed in rotary kilns. The magnesium content of the particulate is taken to be midway between those of the feed and the final product. The levels of emission control for hydroxide and magnesite calcining are estimated at 80 and 95 percent, respectively, for 1970. Recently, the installation of new control equipment has, no doubt, raised these levels of control substantially.[8] The total emission estimate for production of magnesium oxide is 6,463 tons of magnesium into the atmosphere.

5. Magnesium Metal Production

In 1970, the only process for producing primary magnesium was the electrolytic reduction of magnesium chloride to magnesium and chlorine. The precipitated hydroxide (Section 3) is concentrated by filtration, then redissolved in hydrochloric acid to form a much more concentrated solution of magnesium chloride than the original salt brine. This solution is then fed to electrolytic cells for reduction.

In addition to the production of commercial magnesium by this process by a single plant in Texas, between one and three plants in the titanium industry also use the process to recycle magnesium for their own use. The production of chlorine gas from all these processes requires that the emission be well controlled. Even before control, only minute quantities of magnesium would be emitted with droplets in the gas stream. Therefore, it is assumed that emissions from the production of magnesium metal were negligible in 1970.

6. Refining and Alloying

Since molten magnesium reacts vigorously with oxygen and nitrogen, precautions are taken to avoid contact with air. The two methods for doing this are: (1) use of fluxes floated on top of the molten metal in the open pots or crucibles and (2) melting in a closed pot containing sulfur dioxide. No magnesium emissions are expected from the molten metal in alloying. However, magnesium chloride is a basic constituent of the fluxes used with the open pot crucible. The chloride forms magnesium oxide when in contact with water, and slight emission of fluxing magnesium may result. The emission factor of 4 lb/ton is for a pot furnace.[6] The assumption is made that all primary plus secondary magnesium metal (124,000 tons) was refined, alloyed, or smelted by the open pot process. An estimated level of control of 90 percent is based on controls commonly used in alloying and secondary metal refining. The resulting emission estimate is a negligible 15 tons.

7. Refractory Material Production

Fire brick and both wet and dry patching compounds are made in large quantity from magnesia derived from both magnesite and dolomite. After being calcined at 900 to 1700°C, the magnesia is finely ground, classified, and mixed with other brick ingredients such as chromite or clay. To mix well, drying may be necessary. These processes appear to be major sources of emission, although data are scant. Subsequently, the mixture is cast into brick and dried in stationary kilns at low temperatures; or if fused-cast, melted in an electric arc furnace at up to 2500°C and then poured and cast. During the drying in kilns and through the miscellaneous process of handling, the bricks and compounds appear to generate negligible emissions. The electric casting operation is estimated to be a substantial source of emission, however.

Based on emissions estimated for clay refractory materials,[7] and for similar grinding and melting operations, emission factors of 150 lb/ton for all mechanical operations, and an additional 75 lb/ton for melting and casting, are assumed. Of the 483,000 tons of magnesium used

in refractories, it is estimated that about 10 percent is used in patching materials,[11] and that only about 10 percent of the brick is cast, or about 44,000 tons. The level of emission control should be higher than in the case of clay refractories (64 percent) because the materials are more valuable. A level of control of 80 percent for the mechanical processes is assumed, and 85 percent for the electric melting and casting processes. The resulting total emission estimate is 7,500 tons of magnesium emitted to the atmosphere; the largest estimated emission from the magnesium industry.

8. Magnesium Chemicals

Emissions from the production and use of magnesium-based chemicals are estimated to be negligible.

a. Magnesium Chloride

In addition to usage in the production of oxide and metal, MgCl is also used in oxychloride cements for flooring and plaster, as a fireproofing agent for wood, as a dust binder, and in fluxes for alloying. A small segment of the wood pulping industry uses magnesium-based chemicals for separating wood fibers. None of these processes appear to generate emissions of any magnitude.

b. Magnesium Hydroxide

This is used in the pharmaceutical, milk of magnesia, in sugar refining, and by the paper industry. None of these processes appear to generate emissions of any magnitude.

c. Magnesium Carbonate

This is used in the production of insulation for steam pipes; in paints, plastics, and paper; and as a soil conditioner. The total quantity of carbonate consumed is very small.

d. Magnesium Sulphate

This is used as epsom salts, dyes, drying agents for organic solvents, tanning agents, and fireproofing. The total consumption is small.

9. Inadvertent Sources

a. Iron and Steel Production

The iron and steel industries use raw dolomite and limestone (containing small amounts of magnesium) as fluxes in the production of iron and steel. Magnesium metal is also used as a scavenger and deoxidizer. Furthermore, the furnaces and containers used for most molten iron and steel are lined with refractory material, much of which contrains magnesia. Open hearth furnaces require about 10 lb of magnesite brick per ton of steel produced, for example.[11] It is, of course, not expected that all these sources of magnesium will result in emissions from the furnaces. Since magnesium has a much lower vaporization temperature than most of the other elements present, at least some magnesium emission is expected.

Table 1 gives the quantities of iron and steel produced by the major processes, together with generally accepted emission and control factors. Data concerning the amount of magnesium contained in the emission was found to be as follows:

Percentage of Magnesium in Fume

					Range	Est. Ave.
Sintering	0.6-6[a]				0.6-6	3.0%
Blast furnace	0.1-3[a]	2-3.6[b]			0.1-3.6	1.2%
Open hearth	0.2-0.7[a]	0.23[c]	0.1[e]		0.2-0.7	0.3%
Basic oxygen	0.4-0.7[a]				0.4-0.7	0.5%
Electric arc	0.2-9[a]	2-9[d]	9.2,4,8[c]	1.2[e]	0.2-9.2	5.0%

a. Reference 7
b. Reference 12
c. Reference 14
d. Reference 13
e. Reference 15

These Figures indicate a total estimated average of 4,195 tons of magnesium after control.

b. Coal Combustion

Coal consumption in 1970 amounted to 517,000,000 tons.[4] The particulate generated has been estimated at 33,800,000 tons of which 82% was controlled, leaving 6,100,000 tons of emission to the atmosphere.[7] Spectrochemical analysis of 373 samples of coal from across the U.S. indicated an average content of 0.70 percent magnesium in the ash.[16] Thus, it is estimated that 236,000 tons of magnesium before control or 42,600 tons of magnesium after 82 percent control, was emitted into the atmosphere. This is almost six times greater than the next largest source of magnesium identified in this study (refractory production).

c. Oil Combustion

It is estimated that 287,000 tons of particulate are generated by the combustion of residual oils in the U.S. and that this particulate is not under any significant degree of control.[7] The content of magnesium in this particulate has been reported as 0.27 percent (two samples, Ref. 7); 0.053 percent (three samples, optical emission spectroscopy, Ref. 17), and 0.20 percent (one sample, several analytical techniques, Ref. 18). Using an average 0.15 percent, results in an estimated emission of 430 tons.

d. Asbestos

Emissions of asbestos are estimated to have been 6,579 tons in 1970, after control.[7] Chrysolite, the predominant fiber of asbestos, is a silicate of magnesium containing approximately 19 percent magnesium. This results in an estimated emission of 1,250 tons of magnesium in 1970.

e. Cement Production

It is estimated that 934,000 tons of particulate after control were generated from the various processes of cement production in 1970.[7]

Based on limestone, which is distinguished from dolomite in that it contains a low percentage of magnesium, one expects that cement emissions will contain significant, but highly variable amounts of magnesium. Particulate concentrations of magnesium are reported to be: 0.07 percent (three samples of kiln and clinker cooler dust, Ref. 19); 0.4 percent (three samples from air separators, Ref. 19); and 1.15 percent (kiln dust, Ref. 7). Based on these percentages, the range of magnesium emissions is 650 to 10,700 tons/year after 88 percent controls with an intermediate value of 3,730 tons/year.

C. SUMMARY OF PRINCIPAL EMISSIONS

Table 2 summarizes the major sources and estimated emissions of magnesium, as developed in Table 1 and accompanying discussion. The sources are grouped into two categories, those directly originating within the magnesium industry, and those having no relationship to the magnesium industry, called inadvertent sources. The latter category represents about 62 percent of the total estimated emissions. These principal estimates are examined further in section IV of this report.

TABLE 2

SUMMARY OF PRINCIPAL SOURCES AND EMISSIONS OF MAGNESIUM

	U.S. Tons/ Year of Mg	% of U.S.
Inadvertent Sources		
Coal combustion	42,600	56.5
Iron and steel production	4,195	5.6
Magnesium Industry Sources		
Refractories production	7,500	10.0
Magnesite mining and processing	5,790	7.7
Dolomite mining and processing	3,323	4.4
Dolomite calcining, rotary kilns	3,593	4.8
		89.0

IV. REGIONAL DISTRIBUTION OF PRINCIPAL SOURCES AND EMISSIONS

For the purpose of showing geographical distribution, the United States was divided into ten regions identical to the Regional Branches of EPA.

Region	States
I	Conn., Me., Mass., N.H., R.I., Vt.
II	N.J., N.Y., P.R., V.I.
III	Del., Md., Pa., Va., W.Va., D.C.
IV	Ala., Fla., Ga., Ky., Miss., N.C., S.C., Tenn.
V	Ill., Ind., Mich., Minn., Ohio, Wis.
VI	Ark., La., N.M., Okla., Tex.
VII	Iowa, Kans., Mo., Nebr.
VIII	Colo., Mont., N. Dak., S. Dak., Utah, Wyo.
IX	Ariz., Calif., Nev., Hawaii and the South Pacific
X	Alaska, Idaho, Oreg., Wash.

The principal emission sources listed in Table 2 are distributed among these ten regions, as shown in Table 3. Also, the number of plants producing the emissions are shown in the table, when such information is available.

When the estimated number of plants was greater than 100, and the distribution of plants was not known, the regional breakdown was made on a different basis, such as population, geographical area, or shipments reported, as most appropriate for that category. Whether the distribution was by plant size, number of plants, or another statistic, the distribution is believed to be accurate to within 10 percent in most cases.

The accuracy of the distributions by region varies with the category. The number of plants per category varied from one to several thousand in this study. When the number of plants was less than 100, an attempt was made to identify each plant and plant location, and include it in one of the ten regions. When production or capacity figures for these plants were available, total production or capacity for each region was computed,

TABLE 3

REGIONAL DISTRIBUTION OF PRINCIPAL SOURCES AND EMISSIONS

Principal Sources	EPA REGION										TOTAL (units)	Ref.
	1	2	3	4	5	6	7	8	9	10		
Inadvertent Sources												
Coal combustion	298	2428	9,287	8,989	17,422	597	1747	1406	298	128	42,600 (tpy)	
	0.7	5.7	21.8	21.1	41.3	1.4	4.1	3.3	0.7	0.3	100 (% of U.S.)	4
Iron and Steel Production	232	334	1121	395	1477	201	50	20	294	70	4,195 (tpy)	
Magnesium Industry Sources	23	33	111	39	146	20	5	2	29	7	415 (U.S. plants)	20
Refractories production	357	833	2025	357	2975	0	120	357	476	0	7,500 (tpy)	
	3	7	17	3	25	0	1	3	4	0	63 (No. Plants)	21
Magnesite mining	0	0	0	0	0	0	0	0	5790	0	5,790 (tpy)	
	0	0	0	0	0	0	0	0	1	0	1 (No. Plants)	4
Dolomite mining	237	0	475	119	1539	0	119	237	594	0	3,320 (tpy)	
	2	0	4	1	13	0	1	2	5	0	28 (No. (Plants)	22
Dolomite calcining	257	0	513	128	1668	0	128	257	642	0	3,593 (tpy)	
	2	0	4	1	13	0	1	2	5	0	28 (No. (Plants)	22
TOTALS:	1381	3595	13,421	9,988	25,081	798	2,164	2,220	8,094	198	66,997	
	1.8	4.8	17.8	13.3	33.3	1.1	2.9	2.9	10.8	0.3	89.0 (% of U.S.)	

and the U.S. emission estimate for that category was distributed by region accordingly. When production or capacity figures were not available, the emission was distributed by the number of plants in each region. If the number of plants was very small or there was reason to believe that certain plants were larger or produced more emission, distributions were weighted accordingly.

Specifically, the largest emission estimate; i.e., from the combustion of coal, was distributed percentagewise, according to coal shipments in 1970, by state of destination. Emissions from iron and steel production were distributed by total number of iron and steel producing plants, by state. This is an approximation since emissions from certain processes, notably sintering and open hearth steel production, are larger than from other processes. Information is not available as to numbers and sizes of sintering equipment by state in the U.S., nor for open hearth production. It is implicitly assumed that the distribution of these largest emission processes will be similar to that of the overall iron and steel industry.

Emissions from production of magnesium-containing refractories are distributed by number of plants reporting products of that type, by state, as no information as to the relative sizes of the plants was available. Only one plant was engaged in the mining of magnesite in 1970. Nearly all dolomite mining and calcining were done in the same locations, with the possible exception of a small quantity of additional calcining performed by manufacturers of refractory materials to meet their own specifications. Thus, emissions from mining and calcining were distributed in the same way. A map of locations of plants operating rotary kilns for dolomite calcining was obtained from the National Lime Association. The list was supplemented by a list of five additional plants producing dead-burned dolomite, also obtained from the same source. Again, distribution by number of plants does not reflect the relative sizes of the plants, nor the relative cleanliness of their operations.

As a result of these distributions, Region 5 was estimated to release the largest amount of magnesium to the atmosphere,

about 33 percent of the U.S. total. Regions 3 and 4 were next, with another 31 percent combined. These results are largely due to the estimates regarding emissions from coal combustion, which contributed roughly two-thirds of the emissions from each of these regions.

Considering the geographical area of the ten regions, the most concentrated emission of magnesium, averaged over the area, was in Region 3, with 0.11 tons of magnesium per square mile per year, closely followed by Region 5 with 0.075 tons per square mile per year.

V. NATURE OF EMISSIONS

The physical characteristics of the particles emitted to the atmosphere containing magnesium, and the chemical form of magnesium, are the results of the exact process variables, feed materials, and the nature of magnesium itself. Tables 4a and 4b describe some of the important minerals containing magnesium, and some of the properties of the metal. The boiling, or vaporization temperature of the various minerals and of magnesium is probably the most important property from the standpoint of emissions. Processes that exceed that temperature may be expected to generate large fractions of the magnesium compound present, while processes operating at lower temperatures should be relatively non-emitting of that magnesium compound as a vapor.

Magnesium is among the most readily oxidized elements, which is one of the reasons it is used as a scavenger in steel making. It can be expected to form chemical bonds with oxygen and other elements and element groups rather than remain in metallic form. This is highly probable when hot finely divided particulate is exposed to oxygen. Subsequently the oxide may absorb water or carbon dioxide.

The combustion of coal generates the largest emission of magnesium to the atmosphere. The form of magnesium in the coal, before combustion, is not established, but is probably a carbonate. Combustion at temperatures on the order of 1500°C is expected to partially reduce the carbonate to the oxide. Since, however, the oxide has a vaporization temperature on the order of 3600°C, the oxide will probably not be emitted as a vapor, but as an inclusion with the flyash.

Analysis of several sizes of flyash particles for magnesium content showed a uniform 0.6 percent magnesium contained in all particles greater than 1.7 micrometers, and 0.8 percent in particles smaller than 1.7 micrometers.[25] Flyash particles themselves vary in size from submicron to greater than 100 micrometers, but average (mass median) diameters are typically from 3 to 10 micrometers.

TABLE 4a[8,23,24]

DESCRIPTION OF MAGNESIUM MINERALS AND PRODUCTS

Mineral	Formula[a]	Process[b] Temp.	Hardness	Specific Gravity (g/cc)
Brucite	$MgO \cdot H_2O$	Natural	2.5	2.4
Dolomite, raw	$CaCO_3MgCO_3$	Natural	3.5-4.5	2.8-3.0
Dolomite, calcined	---	1100°C	---	---
Dolomite, dead-burned	---	1700°C	---	---
Magnesite, raw	$MgCO_3$	Natural	3.5-4.5	2.95-3.2
Magnesite, dead-burned	---	Same as magnesia		
Magnesia	MgO	Over 1460°C	---	---
Magnesia, caustic calcined	$MgCO_3$ or MgOH	950°C or less	---	---
Magnesium peroxide	MgO_2	---	---	---
Olivine	$(Mg,Fe)_2SiO_4$	Natural	6.5-7.0	3.3-3.4
Periclase	MgO	1700°C (Also natural)	---	3.58

[a] Natural materials include varying amounts of other ingredients.

[b] Temperature required for process completion.

[c] Standard minerology scale of hardness.

TABLE 4b (Ref. 23, Table 3-169)

PROPERTIES OF MAGNESIUM METAL

Melting point:	650°C
Boiling point:	1107°C (MgO boiling point: 3600°C
Density:	1.74 g/cc
Atomic weight:	24.3 a.w.u.
Heat of vaporization:	32.5 kg-cal/g atom

Most of the equipment used to control flyash emissions tends to remove the larger particles and allow the smaller ones to escape. Particles on the order of 1 micrometer and smaller may be expected to travel indefinitely (i.e., tens of miles) before being removed from the air by natural processes (settling, agglomeration, washout, etc.). No physical or chemical changes of the magnesium contained in the particles are expected to take place during this period, except for possible absorption of water or carbon dioxide.

The next largest estimated source of emission, the production of refractory materials, is due mostly to mechanical processes including grinding, crushing, screening and classification, mixing, etc. Grinding may be expected to generate a substantial quantity of particles on the order of 10-micrometer diameter, as well as some on the order of 1-micrometer diameter. The smaller ones will tend to escape, while the larger, if not immediately controlled, will tend to settle in the vicinity of the grinders. The particles that escape will be non-spherical, and will contain magnesium predominantly as an oxide. Screening and mixing operations, being less intensive in terms of the stresses applied to the particles, will tend to emit 10- to 100-micrometer particles and agglomerates, while a relatively small fraction of the material in particles 1 micrometer and smaller will escape the vicinity of the plant.

Emissions from mining and calcining are expected to include both the carbonate and oxide forms of magnesium. The emissions from a concentrate drier ahead of the kiln are reported to be 95 percent less than 5 micrometers, 85 percent less than 3 micrometers, and 10 percent less than 1 micrometer.[8] The literature reports analysis of particulate emitted from 20 dolomite kilns in Russia as follows:[26]

30- to 70-micrometers diameter before control
40 to 50 percent potassium oxide plus magnesium
10^5 to 10^6 megohm-cm electrical resistance

Both calciner or kiln and drier particles are expected to be non-spherical and fairly inert chemically.

Dusts in the vicinity of iron works have been analyzed for particle size distributions and MgO content. The average particle sizes ranged from 1 to 4 micrometers; the MgO content ranged from 3.3 to 6.8 percent. The variation of MgO concentration with particle size was not reported, however.

In conclusion, the sizes and chemical forms of magnesium containing particles are such that most of the particulate emitted without control measures, and a modest fraction of the particulate emitted despite control measures, will probably not travel far from the emission source. However, a large portion of the U.S. emissions of magnesium will exist in micrometer and smaller particles and will travel long distances from the plant. This magnesium is expected to be chemically inert except for some possible absorption.

The magnesium content of city air is reported in one instance as 0.42 (total particulate concentration = 44.7 $\mu g/m^3$) to 7.21 micrograms per cubic meter (total particulate not measured) in particles averaging (mass median diameter) 4.5 to 7.2 micrometers. Between 17 and 23 percent of the mass was contained in particles less than 1 micrometer diameter.[27]

VI. UPDATING OF EMISSIONS ESTIMATES

The following recommendations are made for periodically updating the estimates made in this study:

A. VERIFICATION OF CURRENT ESTIMATES

1. Verify that the estimated concentrations of magnesium contained in emissions from the production of iron and steel are representative. Although the concentrations are small, the tonnages of emissions from these processes are potentially large enough to affect the conclusions of the study, if the concentrations are in fact higher than estimated. If the concentrations prove to be higher, the emissions estimates should be distributed by region, by types of iron and steel processes, rather than number of plants of all types.

2. Verify that the emission factors for the production of refractory materials, and for the calcining of dolomite and magnesite, are representative. The estimates used in this study are based on a limited quantity of data which also showed considerable variation from data source-to-source.

B. PERIODIC REVIEW OF ESTIMATES

1. The Bureau of Mines estimates for material flow, industry practices, and trends provide the best estimates of the size of the industry.

2. EPA activities are currently generating the best emissions data and should be reviewed using:

   a. Overall industry studies (e.g., Reference 25).

   b. The Source Test Program in which specific individual plant emissions are measured. This information provides emission factors for specific examples of typical industrial operations; and also provides some analyses of the particulate usually including trace metal content and particle size.

   c. NEDS (National Emissions Data System) is steadily being enlarged and improved. This system can provide emission factors for specific plants and plant operations, the type of particulate control equipment in use, and the actual, or estimated, control efficiency. The system may eventually be expanded to include description of the emissions.

3. The magnesium industry should be consulted for its opinion and suggestions on the most recently published estimates. This may be best accomplished by interviewing the Magnesium Commodity Specialist, Division of Non-ferrous Metals, Bureau of Mines, in Washington, D.C.; or by interviewing one or more of the principal companies in the industry.

4. The literature should be reviewed, using (a) industrial views as published from time to time in Chemical Engineering, for example and (b) environmental views as summarized in Pollution Abstracts, for example.

5. Individual companies or plants may be approached for opinions, data, or cooperative tests of their own operations. This is a difficult approach to the problem of obtaining fresh information due to the natural reluctance of the plants to discuss environmental problems. However, data thus obtained have a relatively high degree of reliability.

6. State agencies in which specific plants are located may be able to provide useful information, and should be contacted.

VII. REFERENCES

1. 1971 Engineering and Mining Journal International Directory of Mining and Mineral Process Information, Mining Information Services, New York (1971).

2. Preprint from Mineral Yearbook,"Magnesium Compounds," U.S. Bureau of Mines, Washington, D.C. (1971).

3. 1971 Statistical Abstracts, U.S. Dept. of Commerce, Washington, D.C. (1971).

4. Minerals Yearbook, 1971, U.S. Bureau of Mines, Washington, D.C. (1971).

5. Hazel B. Comstock,"Magnesium and Magnesium Compounds, A Material Survey," U.S. Bureau of Mines Information Circular IC 8201, Washington, D.C. (1963).

6. "Compilation of Air Pollutant Emission Factors," U.S. Environmental Protection Agency, AP-42, Research Triangle Park, N.C. (1972).

7. A.E. Vandergrift, et al., "Particulate Pollutants Systems Study," Handbook of Emission Properties, Vol. III, Midwest Research Institute, Kansas City, Mo. (1971).

8. Personal Communications with members of the Magnesium industry.

9. Oliver Bowles, "Limestone and Dolomite," U.S. Bureau of Mines Information Circular IC7738, Washington, D.C. (1956).

10. NEDS (National Emissions Data System) data was used to supplement data more readily available in the literature.

11. D.J. Kusler and R.G. Clarke, "Impact of Changing Technology on Refractories Consumption," U.S. Bureau of Mines Information Circular No. 8494 (1970).

12. V. Masek, "On the Composition of Dusts on Work Locations and in the Near Vicinity of Iron Works," Staub, 31(2), 27 (Feb. 1971).

13. W.W. Campbell and R.W. Fullerton, "Development of an Electric Furnace Dust Control System," JAPCA, 12(12), 574 (Dec. 1962).

14. Southern Research Institute, Birmingham, Ala.,"A Manual of Electrostatic Precipitator Technology," Report to NAPCA (EPA), Contract No. CPA-22-69-73 (August 1970).

15. Public Health Service, U.S.D.H.E.W., Air Pollution Engineering Manual, 99-AP-40 (1967).

16. R.F. Abernathy, et al., "Major Ash Constituents in U.S. Coals," Bureau of Mines, U.S. Dept. of the Interior, Report of Investigation No. 7240 (1969).

17. A. Levy, et al., "A Field Investigation of Emissions From Fuel Oil Combustion for Space Heating," Report by Battelle Institute, Columbus, Ohio, to American Petroleum Institute, API Proj. No. SS05 (1 Nov. 1971).

18. D.J. Lehmden, R.H. Jungers, and R.E. Lee, "The Determination of Trace Elements in Coal, Flyash, Fuel Oil, and Gasoline," Part 1. Presented at the American Chemical Society Meeting, Dallas, Texas (April 1973).

19. Source Test Reports of emissions from specific industrial operations, obtained in part from EPA.

20. American Iron and Steel Institute, "Iron and Steel Producing and Finishing Works of the U.S.," a table in the Directory of Iron and Steel Works of the U.S. and Canada (1970).

21. Product Directory of the Refractories Industry in the U.S., The Refractories Institute, Pittsburgh, Penn. (1968).

22. Commercial Lime Plants in U.S. and Canada (Map), National Lime Association, Washington, D.C. (1970).

23. Perry's Chemical Engineers Handbook, 4th Edition, McGraw Hill Inc., New York (1963).

24. "Mineral Facts and Problems 1970," U.S. Bureau of Mines Bulletin 650, Washington, D.C.

25. R.E. Lee, "Trace Metals in Fly Ash as a Function of Particle Size," a single page unpublished table, obtained via R.E. Lee, Research Triangle Park, N.C. (EPA).

26. L.C. Chally, "Physics - Chemical Properties of Dust in Waste Gases During Firing of Refractory Raw Materials in Rotary Kilns," Stal, 30(10), 931, Oct. 1970 (Russian), English abstract, APTIC No. 28311.

27. R.E. Lee, et al., "Particle Size Distribution of Metal Components in Urban Air," Env. Sci. and Tech., 2(4), 288 (April 1968).